Characterizing Variability in the Distribution of High-Frequency Acoustic Backscattering in a Shallow Water Coastal Region

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LONG-TERM GOALS

The central goal of this project is for the Primary Investigator, Gareth Lawson, to design, execute, and defend his doctoral thesis research. In terms of its scientific purpose, this research seeks to contribute to our understanding of spatial and temporal patchiness in the distribution of high-frequency acoustic volume backscattering stemming from zooplankton (e.g., Figure 1).

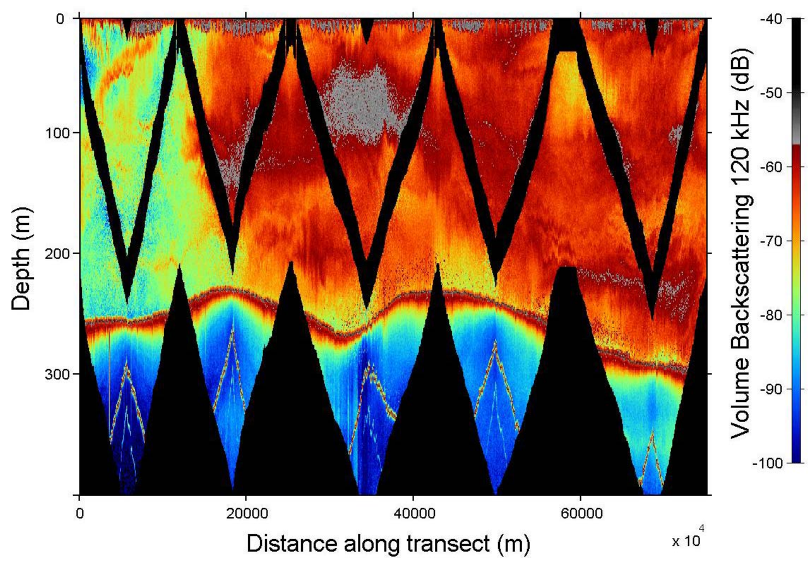

Figure 1: Volume backscattering strength (dB) measured at 120 kHz in Georges Basin, December 1999, showing distinct spatial patchiness both along-transect and with depth.

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OBJECTIVES

The objectives of the project are three-fold: 1. To quantify the spatial and temporal variability in the distribution of acoustically-inferred zooplankton biomass in shallow water coastal regions. 2. To assess the predictability and persistence of such patchiness, and understand its association with physical and biological oceanographic processes. 3. To continue the process of field-testing and refining models of zooplankton acoustic scattering.

APPROACH

The overall approach is to apply the models of zooplankton scattering developed at Woods Hole Oceanographic Institution (WHOI) to multi-frequency volume backscattering data collected in continental shelf regions under other research projects, in order to infer zooplankton abundance and biomass by size group. These estimates of zooplankton abundance and distribution are then compared between times and regions to assess patterns in variability. The areas under study include a continental shelf region west of the Antarctic Peninsula and the Gulf of Maine. At both sites, the data used for analysis were collected with the WHOI BIo-Optical Multi-frequency Acoustical and Physical Environment Recorder (BIOMAPER-II).

Initial investigations and work with collaborators indicated that in many situations, particularly in the Gulf of Maine, the zooplankton community is comprised of such a variety of scatterer types that this process of making quantitative estimates of zooplankton abundance is difficult or even infeasible with only the four frequencies available on the BIOMAPER-II. The primary emphasis of the project therefore shifted to variability in the distribution of krill (primarily *Euphausia superba* and *E. crystallorophias*) in the Antarctic study region. These animals form mono-specific aggregations of uni-modal length distribution, making the estimation of biological quantities from four-frequency acoustic data a much more straightforward problem.

An important aspect of the research has involved the development and verification of protocols for distinguishing the scattering of krill from other zooplankton taxa, delineating krill aggregations within the acoustic record, and estimating the size, abundance, and biomass of aggregation members. These methodologies were then applied to broad-scale survey data collected in the Antarctic under the Southern Ocean Global Ecosystem Dynamics (GLOBEC) program. The resulting measurements of krill distribution and aggregation structure were compared between times and regions, and examined in light of other physical and biological processes studied concurrently during the cruises.

WORK COMPLETED

This award was given to allow the Primary Investigator, Gareth L. Lawson, to pursue his doctoral research, with the Co-Primary Investigators, Timothy K. Stanton and Peter H. Wiebe, acting as thesis advisors. In this fourth year of the project, Gareth completed and defended his doctoral dissertation. The majority of the project is complete and the only outstanding tasks involve the preparation of one further manuscript and presentations to be given at upcoming meetings.

Much of the initial work of the project made use of existing scattering models and parameterizations for interpreting observed backscattering levels. In the case of Antarctic krill, however, an investigation was made into improving the parameterization of a Distorted-Wave Born Approximation-based scattering model. Particular attention was given to the parameters governing the orientation of the animal relative to the incident acoustic wave and its acoustic material properties: parameters that have important effects on predicted scattering, but about which there has historically existed a great deal of uncertainty. Direct measurements of the orientation of krill made with a Video Plankton Recorder were used to constrain the parameter governing the orientation of the animal. Recently published length-based regressions were used to constrain the material properties, rather than the earlier approach of using single parameter values for all lengths. A paper stemming from these investigations was published this year in the Journal of the Acoustical Society of America.

Analyses conducted during the project's first year of expected backscattering levels predicted from depth-stratified net samples made at the Antarctic study site suggested that observed backscattering often stemmed from a complex mixture of zooplankton taxa, but that certain features were acoustically dominated by krill. In contrast, collaborative work with Andone Lavery of WHOI suggested that acoustic measurements made in the Gulf of Maine were only rarely attributable to a unique dominant zooplankton scatterer. The present project has thus come to focus on krill at the Antarctic study site. Methods were therefore required for identifying krill aggregations on the basis of multi-frequency acoustic data alone, without recourse to net samples, and then estimating krill length, abundance, and biomass. A threshold level of volume backscattering strength for identifying krill aggregations was consequently derived on the basis of krill visual acuity. Differences in mean volume backscattering strength at 120 and 43 kHz further served to distinguish krill from other sources of scattering. An inverse method was developed to estimate the mean length and numerical density of krill in these acoustically-identified aggregations on the basis of measurements of mean volume backscattering strength (43, 120, 200, and 420 kHz). Measurements were also made of certain features (e.g., position, shape, internal structure) of the identified krill aggregations. These methods represent a refinement of pre-existing protocols and methods developed during the project's second and third years, and were verified with Video Plankton Recorder observations as well as net catches from a 1-m^2 Multiple Opening/Closing Net and Environmental Sensing System (MOCNESS).

These various methodologies were then applied to broad-scale survey data collected in the Antarctic study region, in order to examine variability in krill distribution and make inferences concerning the forces and behaviors underlying krill aggregation. A paper describing the acoustic methodologies and variability in the distribution of krill has been submitted to Deep-Sea Research Part II and a second manuscript concerning aggregation structure and behavior is currently in preparation.

In addition to the main thesis project, the Primary Investigator was involved in a number of collaborations, including studies on the distribution of higher predators (seabirds, seals, and whales) in relation to their zooplankton prey, and an examination of the genetic composition of krill patches. One paper based on a comparison of whale distribution to zooplankton volume backscattering has been published in Marine Ecology Progress Series and one manuscript comparing bird distribution to krill biomass has been submitted to Deep-Sea Research Part II.

RESULTS

Analyses of the broad-scale distribution of zooplankton backscattering in the Antarctic continental shelf study region revealed strong seasonal and spatial variability during the falls and winters of 2001 and 2002, much of which appears to be understandable in light of meso-scale circulation. Four general types of scattering features were evident across the region: 1) large bottom-associated patches found in regions of variable bathymetry in coastal regions, 2) smaller discrete patches found primarily in the surface mixed layer across much of the shelf, 3) deep diffuse patches found near the shelf-break and northern shelf region, and 4) deep homogeneous scattering layers situated over the southern portion of the study area. On the basis of the multi-sensor methodologies described above, the first two feature types appear to stem from aggregations of krill. Measurements of target strength and net catches from a 10-m^2 MOCNESS trawl suggest that myctophid fishes are the dominant scatterer in the third feature type. The available evidence concerning the deep southern scattering layers is less conclusive. These layers appear to consist of a quite complex mixture of zooplankton taxa, perhaps dominated by copepods and gas-bearing siphonophores.

Similar analyses of multi-frequency volume backscattering data collected in the Gulf of Maine during the falls of 1997-1999 have revealed strong inter-annual and spatial variability, both of which differed between acoustic frequencies. Mean backscattering levels did not reflect the decrease in the abundance of the ecologically-important copepod *Calanus finmarchicus* observed in net catches in the fall of 1998 relative to the falls of 1997 and 1999. An increase in the abundance of the predators and competitors of *C. finmarchicus* may have served to keep backscattering levels high during this period. Distinct patterns and diel changes were evident in the vertical distribution of backscattering, although these differed between basins and years.

As indicated above, theoretical model predictions of Antarctic krill target strength are strongly influenced by the parameters governing the animal's orientation and acoustic material properties. The investigation seeking improved parameterization of a theoretical scattering model for krill found that krill oriented themselves mostly horizontally. Parameterizing the scattering model with the observed distribution of orientations, together with recently published information on krill acoustic material properties, resulted in predictions of target strength more consistent with *in situ* measurements of krill target strength than earlier parameterizations (Figure 2). These predictions were smaller, however, than expected under the semi-empirical model traditionally used to estimate krill target strength (Figure 2). Use of this semi-empirical model in estimating krill abundance thus could result in estimates too low by a factor of at least 2.75.

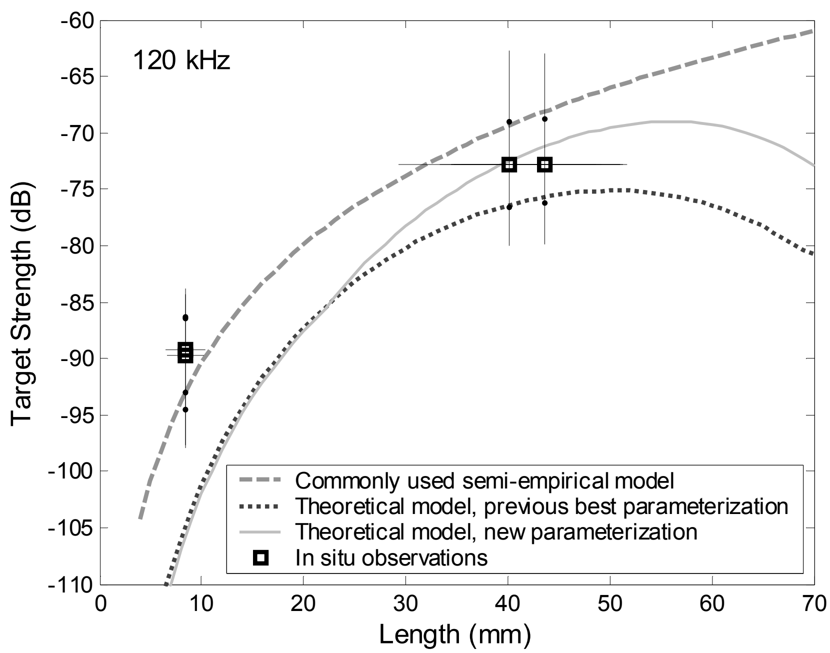

Figure 2: Antarctic krill target strength (dB) at 120 kHz in relation to animal length.

Substantial attention was devoted to verifying the methods employed for distinguishing krill from other sources of scattering and estimating krill length and abundance. For those cases where independent confirmation of the presence of krill was available from net samples or Video Plankton Recorder observations, the difference in volume backscattering strength between 120 and 43 kHz fell within the range ascribed to krill by previous studies. Comparison of the results of the inverse analysis to net samples were favorable in the case of estimated krill length (within a margin of error of 3-12%), but acoustic estimates of krill numerical density exceeded those from nets by one to two orders of magnitude, likely due to avoidance and differences in the volumes sampled by the two systems. The potential for multi-frequency data and mathematical inverse techniques to be used for the simultaneous and quantitative estimation of zooplankton abundance and size has been known for some time, but to the best of our knowledge, this project marks the first time that such methods have been applied to broad-scale data from Antarctic krill surveys.

Application of these methods to the Antarctic multi-frequency survey data demonstrated strong seasonal, inter-annual, and spatial variability in the distribution of krill biomass. The distribution of krill aggregations was characterized by many small aggregations closely spaced relative to one another, punctuated by much fewer aggregations of very large size that accounted for the majority of overall biomass in the region (Figure 3). During fall, biomass estimates vertically-integrated over the sampled portion of the water column were negatively associated with chlorophyll a concentrations, and highest biomass was often observed in regions of lowest current magnitude and horizontal current shear. Generalized additive models indicated that high krill biomass was consistently associated with regions close to land where the temperature maximum below 200 m in depth was cooler than was available over the shelf as a whole. Krill were thus not associated with regions where intrusions of warm and nutrient-rich circumpolar deep water onto the shelf were present at depth, despite such intrusions being thought to be an important driver of primary productivity.

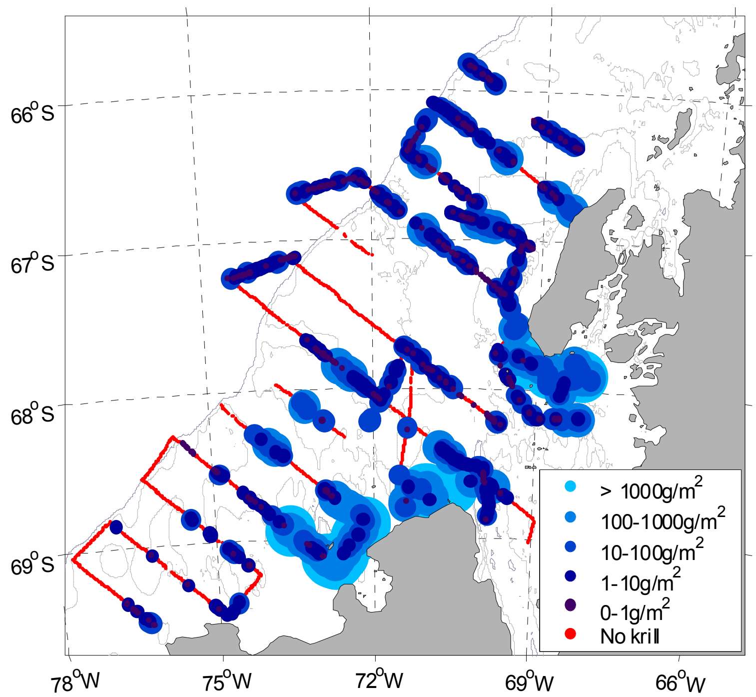

Figure 3: Distribution of Antarctic krill in fall 2001 along the Western Antarctic Peninsula. Dot size and color indicate estimates of krill along-track biomass (g/m²).

Finally, the morphology, internal structure, and vertical position of individual krill aggregations were examined in relation to a variety of properties of the physical and biological environment, allowing a number of interesting ecological insights. Most notably, krill aggregations were observed to exhibit diel changes in vertical position and biomass density (Figure 4); such diel vertical migrations had not previously been observed for krill during winter. Concurrent observations of chlorophyll *a* concentrations and the occurrence of predators, including whales, seals, and penguins, together reinforced the conclusion that aggregation and diel vertical migration represent strategies to avoid visual predators, while also allowing the krill access to shallowly-distributed food resources.

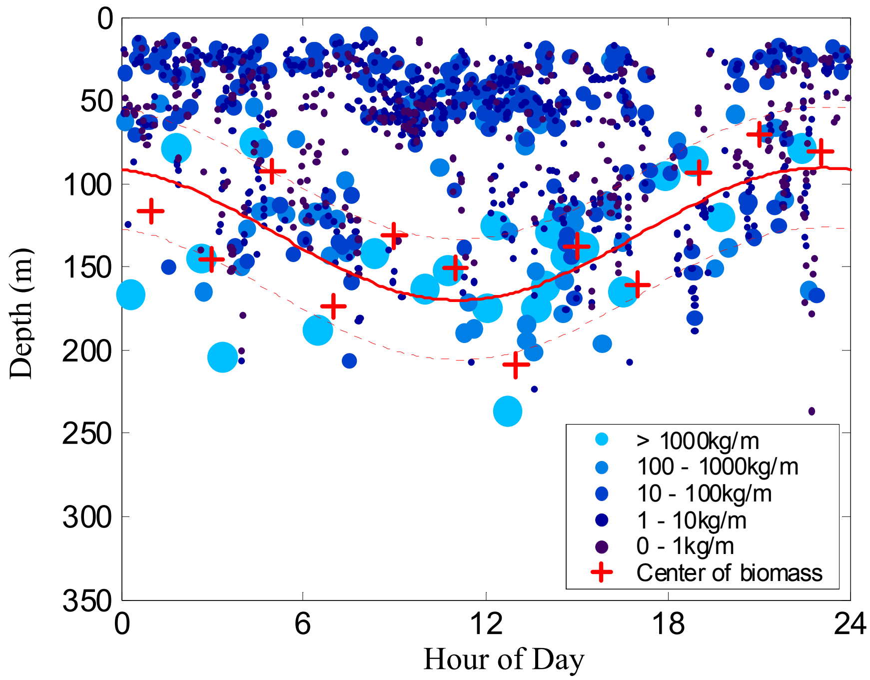

Figure 4: Vertical distribution of krill aggregations in fall 2001 along the Western Antarctic Peninsula. Dot size and color show an index of aggregation total biomass (g/m). Red lines show the inferred diel vertical migration and 95% confidence interval.

IMPACT/APPLICATIONS

The project has resulted in a detailed understanding of variability in the distribution of zooplankton backscattering, particularly in the case of Antarctic krill. Ultimately this should allow such variability to be modeled and predicted. This constitutes an essential step in constraining the uncertainty introduced into Navy representations of the acoustic field by these important scatterers and in understanding the implications of zooplankton patchiness relative to the distribution of predators, including marine mammals and exploited fish species. Much of the present research has made use of existing scattering models. Through comparisons of acoustic data to video and net samples, an approximate model for Antarctic krill has been further evaluated and better parameterized. The outcome is a field-tested acoustic scattering model of a complex, naturally occurring scatterer.

RELATED PROJECTS

The development of the BIOMAPER-II and its use in a series of cruises in the Gulf of Maine were funded in part by the ONR (Grant Numbers N00014-95-11102, N00014-98-1-0362, and N00014-97-1-0646), and in part by NOAA (Grant 31654-5717). Additional data under analysis were collected with the BIOMAPER-II in the Antarctic, as part of the Southern Ocean GLOBEC program (NSF Office of Polar Programs Grant OPP-9910307). Some of the methodologies developed in the present project are also being applied to data collected during the U.S. Georges Bank GLOBEC program, as part of synthesis analyses funded by NOAA (Cooperative Institute for Climate and Ocean Research Grant NA17RJ1223). The zooplankton scattering models employed in the project were originally developed under a number of ONR-funded projects (primarily Grant N00014-95-1-0287).

PUBLICATIONS

Lawson, G.L., P.H. Wiebe, C.J. Ashjian, D. Chu, and T.K. Stanton. 2006. Improved parameterization of Antarctic krill target strength models. Journal of the Acoustical Society of America, 119: 232-242. [published, refereed]

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HONORS/AWARDS/PRIZES

Outstanding Student Paper Award to G.L. Lawson, American Society of Limnology and Oceanography/American Geophysical Union Ocean Sciences Meeting, 2006.